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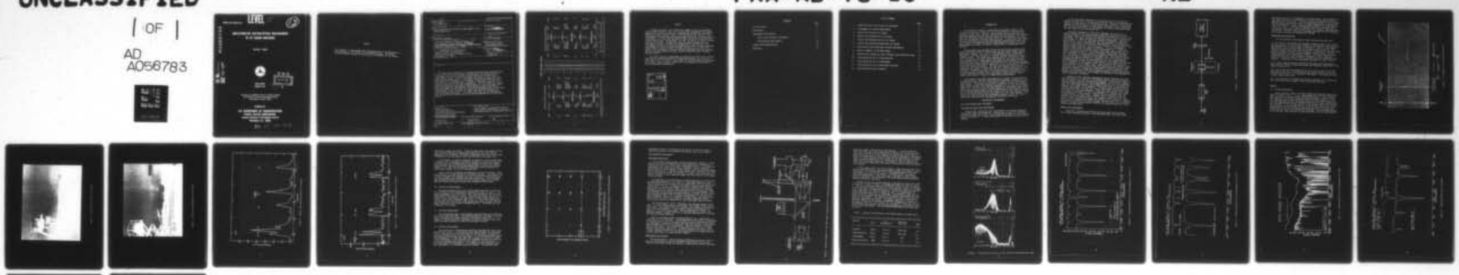

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NON-EXTRACTIVE ELECTRO-OPTICAL MEASUREMENT OF JET ENGINE EMISSIONS

WILLIAM F. HERGET

DEPARTMENT OF TRANSPORTATION
UNITED STATES OF AMERICA

FINAL REPORT
JANUARY 1978

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16. Abstract

A series of measurements of jet engine emissions were conducted in an airport environment using several infrared gas-filter correlation (GFC) instruments and a high resolution Fourier-transform infrared (FTIR) spectrometer system. The GFC instruments were shown to be suitable for measuring CO concentrations in the general airport environment and across the exhaust of a stationary jet. Attempts to determine jet plume rise velocity from the GFC data were unsuccessful. The FTIR system was used to make both absorption and emission measurements on single jets and to make long-path absorption measurements in the general airport environment. Species observed in the single jet absorption measurements were CO (28 ppm), formaldehyde (1 ppm), ethylene (3.2 ppm), and cumulative hydrocarbons (8.6 ppm hexane equivalent). This report describes the instrumentation and the measurement programs and gives some recommendations for additional work.

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Remote Sensing
Jet Engine Emissions
Fourier-Transform Interferometry
Gas-Filter Correlation
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METRIC CONVERSION FACTORS

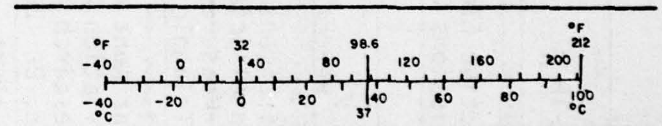
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

The work described in this report was funded in part by the Federal Aviation Administration (FAA) and in part by the Environmental Protection Agency (EPA), and was carried out in cooperation with the Air Force Civil Engineering Center (AFCEC), Tyndall Air Force Base (AFB), Florida. The measurements of carbon monoxide concentrations using gas-filter correlation instruments at Williams AFB, New Mexico, were carried out principally by Science Applications, Incorporated, La Jolla, California, as Task 13 of EPA Contract 68-02-1798. The funds for this task were provided for by an interagency agreement (FA77WAI-744) between the FAA and the EPA. The measurements of various pollutants concentrations using a Fourier-transform interferometer system at Tyndall AFB were carried out by Dr. William F. Herget, EPA, Environmental Sciences Research Laboratory, Emissions Measurement and Characterization Division, as part of the Division's in-house research program.

The author wishes to acknowledge in particular the work of Mr. Richard Yoder and Mr. Edward Meckstroth of Science Applications, Inc., and the assistance of Mr. Carl Zeller, then of EPA, in the Williams AFB measurements, and of Capt. Harvey Clewell, Tyndall AFB, for arranging and assisting in the interferometer measurements.

CONTENTS

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INTRODUCTION

The conventional method of monitoring air pollutant levels in the vicinity of airports involves the use of point sampling instrumentation located at fixed sites. However, various remote sensing techniques that have been developed over the last few years have the potential of providing much more information about pollutant levels and distributions than that which can be obtained from point sampling sites. In particular, the remote sensing instrumentation provides path-averaged concentrations (which are more suitable for comparison with pollutant dispersion models) and allows measurements to be made in locations inaccessible to conventional point monitors.

Three programs have now been carried out at military airports using several different types of infrared long- and short-path remote sensing measurement systems. The first of these programs, which is described in Reference 1, involved the use of a long-path infrared absorption spectrometer system. This system had a maximum spectral resolution of about 1 cm^{-1}, and the only pollutant species observable at this resolution was carbon monoxide (CO). Measurements were made over pathlengths of 500 to 2000 meters at various locations around Williams AFB, and the path averaged CO concentrations were found to range from 0.5 to 1.0 ppm during periods of normal jet aircraft operation. The other two programs, which are the subject of this report, involved the use of (1) three non-dispersive infrared (NDIR) insturments to make long- and short-path CO measurements at locations similar to those used in the above referenced program; and (2) a Fourier-transform infrared (FTIR) spectrometer system that was used at Tyndall AFB to make a variety of remote sensing measurements.

The purpose of the NDIR measurements was to assess the applicability of these relatively low-cost remote sensing instruments to measure CO concentrations in the vicinity of taxiways at various locations and heights above ground. A secondary purpose was to determine if short-path measurements across taxiways could provide information on the rate of jet exhaust plume rise. The aim of the FTIR measurements was to determine what information on jet exhaust species could be determined by high-resolution (0.125 cm^{-1}) infrared spectroscopy and what effect the high noise levels produced by the jet engines would have on the operation of the interferometer. This report will describe these two measurement programs, assess the results, and discuss some additional measurement that would be of value.

EXPERIMENTAL MEASUREMENTS

GAS-FILTER CORRELATION INSTRUMENTS

Principles of Gas-Filter Correlation

A gas-filter correlation (GFC) spectrometer is an advanced type of conventional NDIR instrumentation. Descriptions of specific instruments are given in References 2 and 3, and a detailed discussion of the theory is given in Reference 4. A simple description of the basic principles of GFC follows.

A GFC spectrometer depends for its sensitivity on the correlation between the structure in the spectrum of the gas species to be measured and that of the same species in the correlation cell. Generally, the spectral bandpass of the instrument includes several absorption lines so that there will be large fluctuations in transmittance at different wavelengths when the beam traverses the correlation cell.

An optical diagram of a simple GFC instrument is shown in Fig. 1. Radiant energy from the source passes through the sample area into the instrument, where it then passes through either the correlation cell or the attenuator. The sample area may be a factory stack or duct, a closed cell with windows, or simply an open path through the atmosphere. When the sample area is void of any absorbing gas, the attenuator is adjusted so that the total energy transmitted by the attenuator is equal to the total energy transmitted by the correlation cell (over the filter bandpass); the detector output then has a zero ac component. This null condition is simple to obtain when the sample area is an evacuable cell. (When the sample area cannot be purged of the gas under study, determining the null setting becomes difficult.) When the gas under study enters the sample area, the amount of energy reaching the detector through the attenuator will decrease due to absorption in the sample area. The amount of energy reaching the detector through the correlation cell will be essentially unchanged because the gas in the correlation cell has already absorbed those wavelengths at which the gas under study (in the sample area) absorbs. The ac component of the detector output then increases with increasing concentration of the gas under study. The magnitude of the detector signal resulting from a given pollutant concentration also depends on the source brightness, detector responsivity, efficiency of optical components, etc. However, the fractional difference between the energy reaching the detector through the correlation cell and through the attenuator is not dependent on these instrumental parameters.

Probably the most important advantage of the GFC technique over other NDIR techniques is its ability to discriminate against particulate matter and gas species other than the one being measured. Particles will generally attenuate energy equally at different wavelengths over the filter bandpass. Thus, to a good approximation, the presence of particles in the sample area produces no ac signal at the detector. Particles effect the total energy reaching the detector, but not the ratio of the signals transmitted by the correlation cell and the attenuator. Gases other than the one under study that absorb in the region of the filter bandpass will produce no ac signal at the detector if their spectral structure has no correlation with the structure of the gas under study. However, there is generally some correlation, and the interfering gases will produce a small positive or negative ac signal, depending on whether the correlation is positive or negative. The use of a fixed-position grating assembly with multiple slits to transmit carefully selected narrow spectral intervals can greatly reduce this interference from other gases.

Specific GFC Instruments

Three GFC instruments sensitized for CO were used in this program. Two of these instruments operate in the absorption mode; the light source

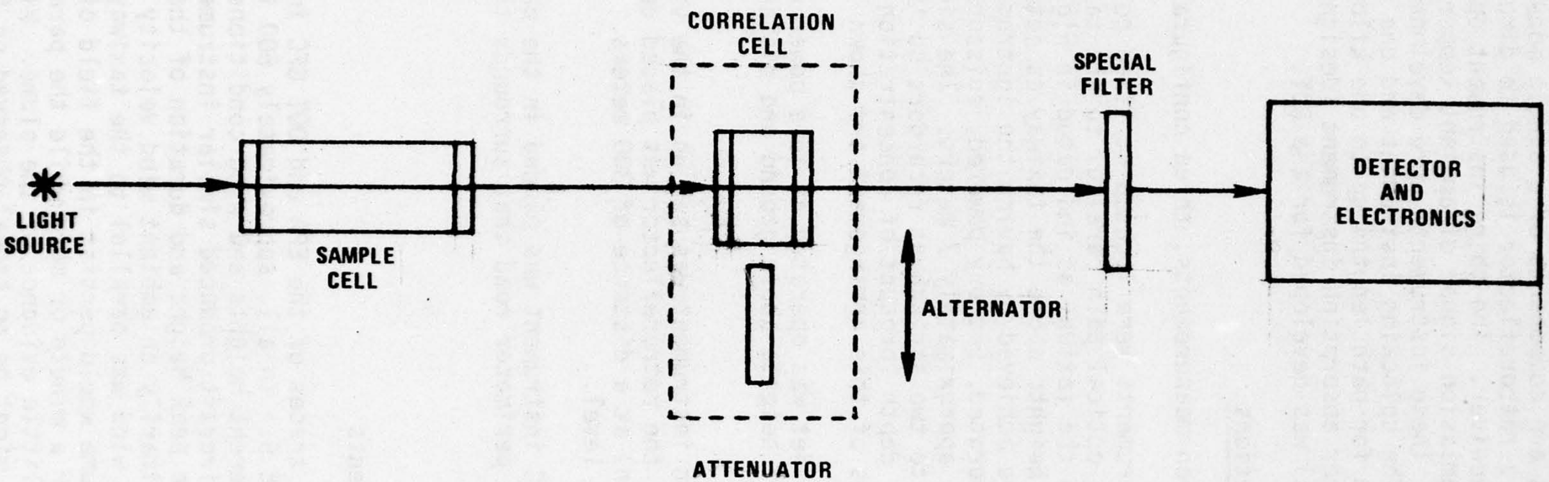

Figure 1. Simplified Gas-Filter Correlation Instrument.

and receiver sections are components of a single module, the atmosphere is the sample area, and a retroreflector is used to direct energy from the source back to the receiver. The third instrument operates in an uplooking mode and senses the emission signal of ambient temperature CO against the cold sky background. These instruments were developed by Science Applications, Inc. (SAI). The uplooking instrument and one of the absorption instruments (designed for path lengths up to one kilometer) were developed for the EPA. The other absorption instrument (designed for path lengths of up to about 40 meters) was developed for the DOT.

Measurement Configurations

For the absorption measurements, three configurations were used:

(1) The two GFC instruments were located at fixed positions on an active taxiway, one with its optical path parallel to the taxiway and one with the path perpendicular to the taxiway as indicated in Figure 2. Measurements were made at various heights above the taxiway as jets taxied by. The different heights were achieved by having the instruments and retroreflectors placed on manually operated, battery powered, scissors jacks. Maximum height obtainable was approximately 7 meters. The signal outputs of the instruments were fed to two stripchart recorders so that a continuous readout of CO optical depth (product of concentration and pathlength) was obtained. Photographs of this arrangement are shown in Figures 3 and 4.

(2) A single captive jet was operated at idle power while measurements were made at different heights above ground and distances downstream of the engine exhaust plane.

(3) The EPA long path instrument was set up in the vicinity of the base operations office and the retroreflector was placed due east (across the aircraft parking apron) at a distance of 300 meters. The optical path was 4 meters above ground level.

(4) The uplooking GFC instrument was placed in the back of a pickup truck and driven around the perimeter road that surrounds the base.

Results

(a) Taxiway measurements

Typical recorder traces of the EPA and DOT GFC instrument outputs are shown in Figures 5 and 6. In all, approximately 500 total jet traversals were measured at different heights and wind conditions. It was observed that identical type aircraft produced similar instrument outputs. It was also observed that the peak height and duration of the signal caused by a jet plume depended primarily on ambient wind velocity (speed and direction). As an example, if the wind was parallel to the taxiway with planes taxiing into the wind, the plume would persist in the field of view of the cross-taxiway path (CTP) for a minute or more while the parallel-taxiway path (RTP) would see very little evidence of the plume. With wind perpendicular to the taxiway, there might be no signal observed on the CTP while the PTP

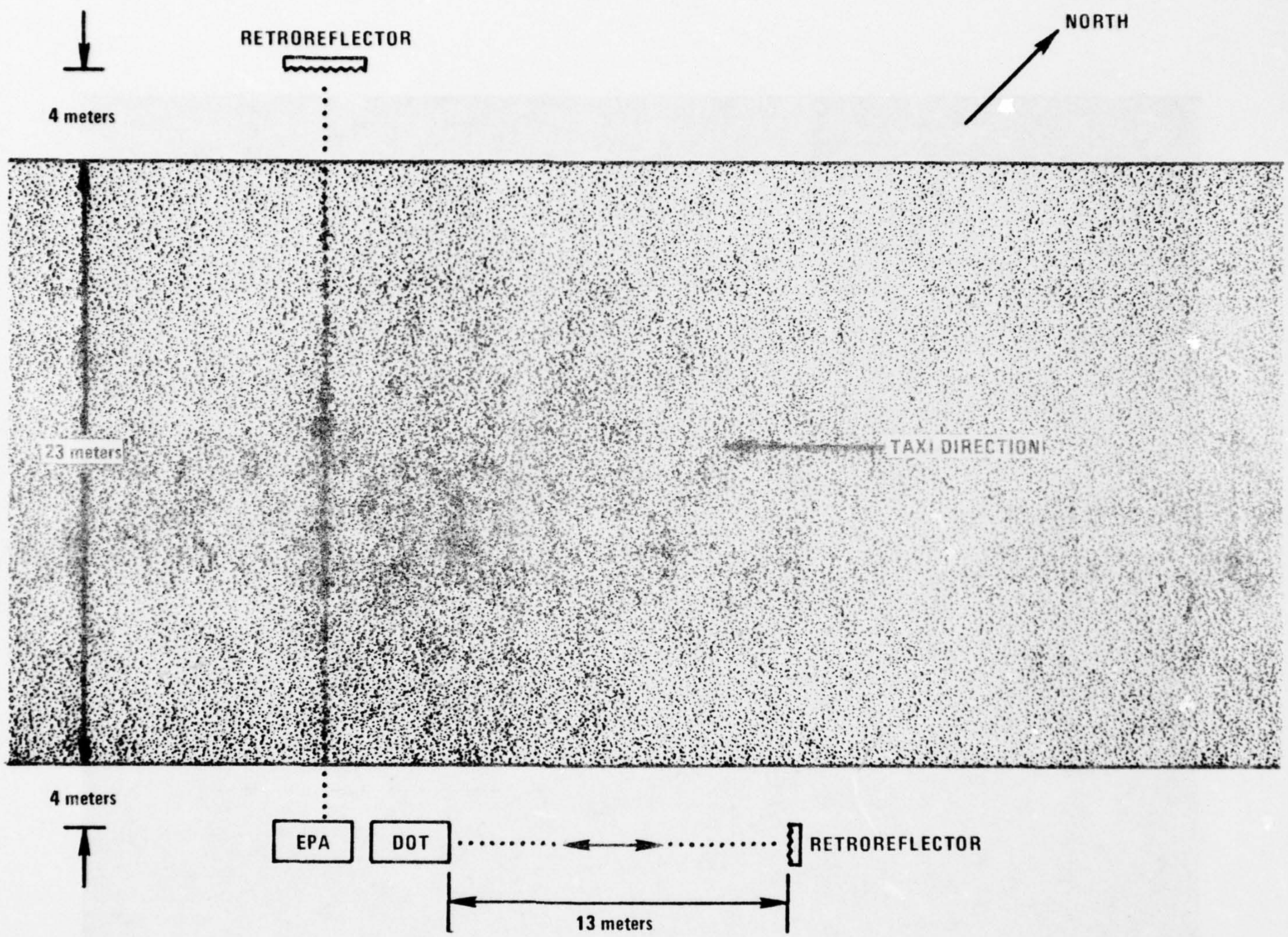

Figure 2. Arrangement for Taxiway Measurements.

Figure 3. Optical Path Parallel to Taxiway.

Figure 4. Optical Path Perpendicular to Taxiway.

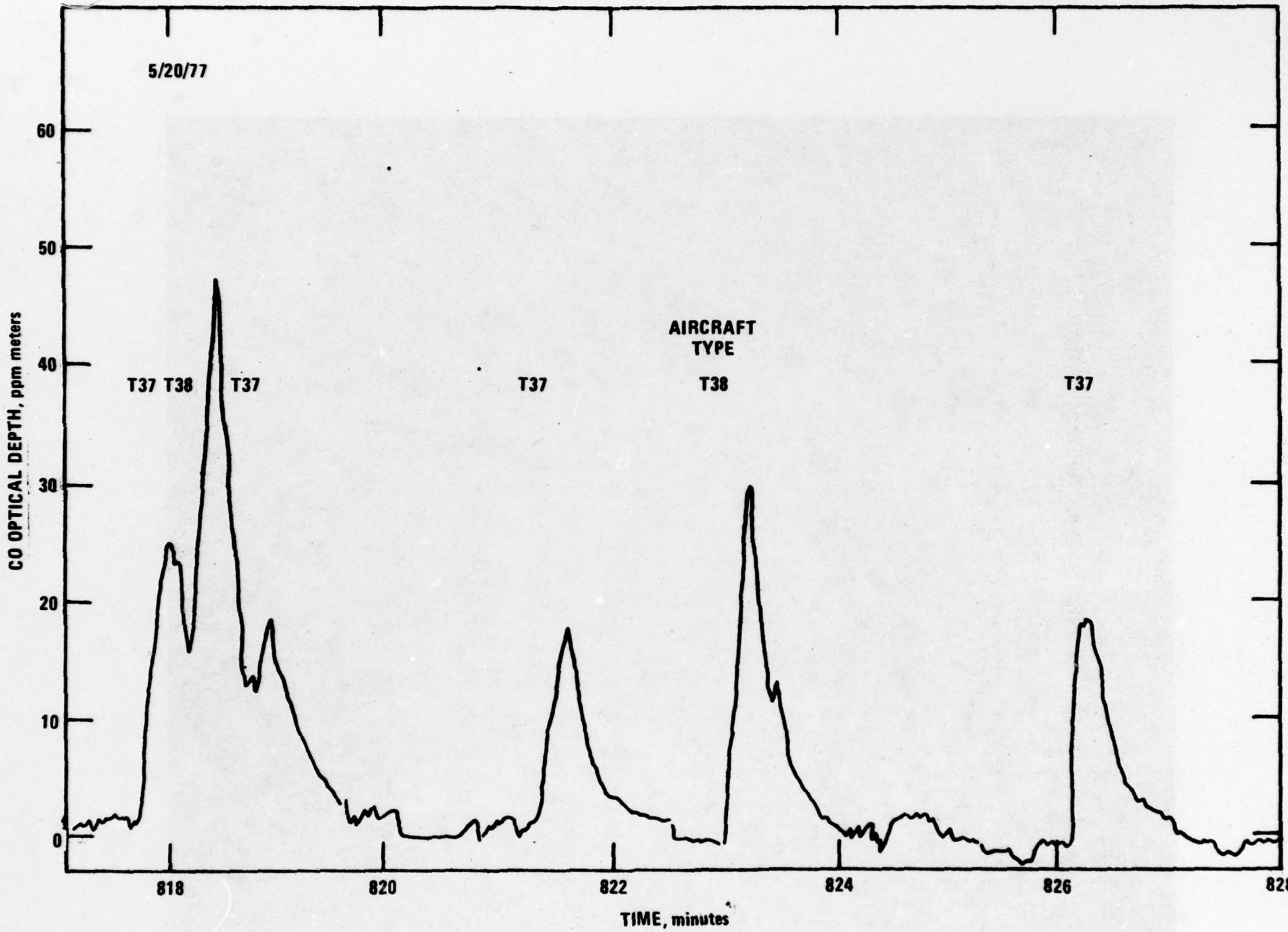

Figure 5. Typical Data Obtained Parallel to Taxiway.

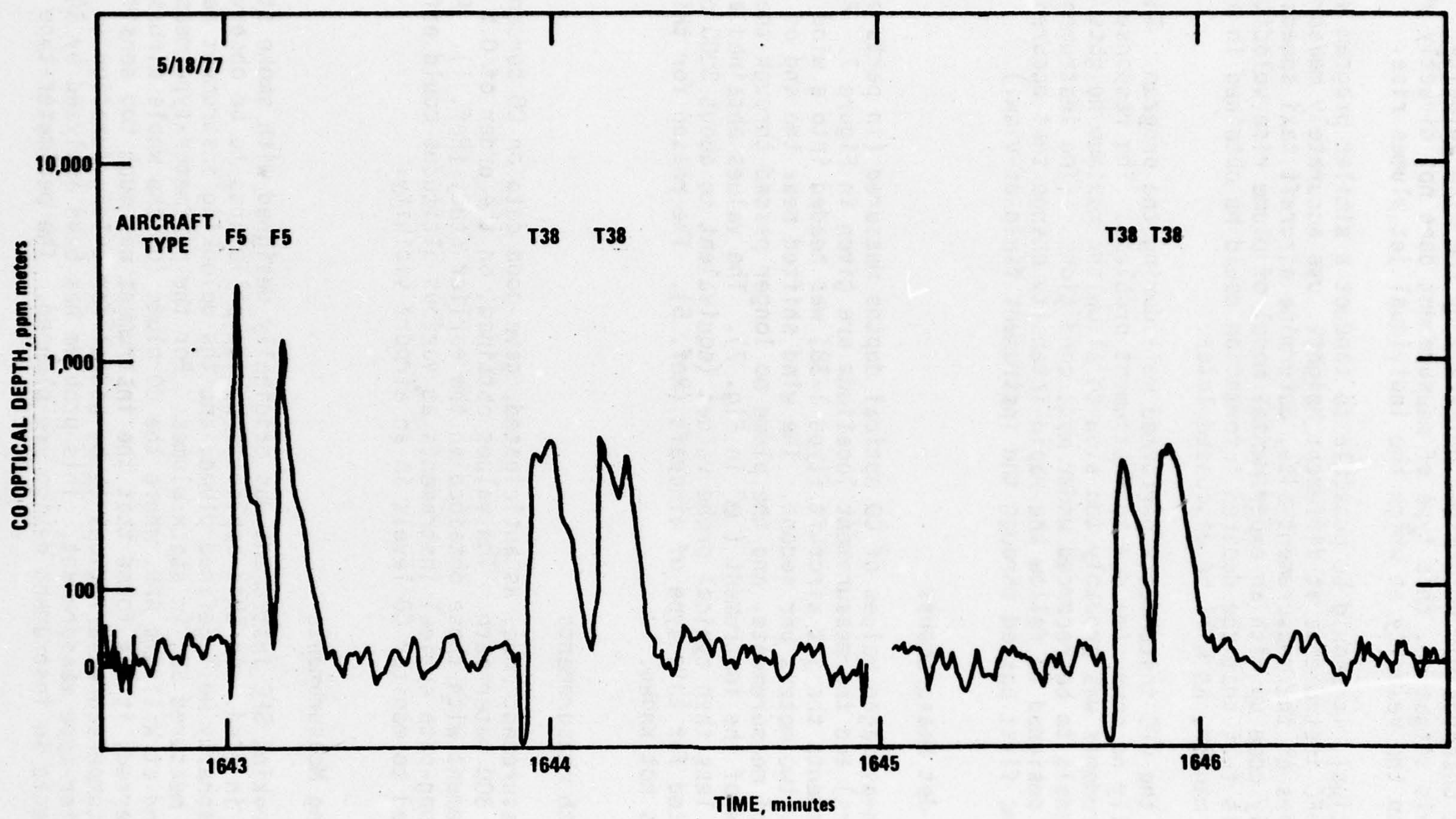

Figure 6. Typical Data Obtained Perpendicular to Taxiway.

would easily detect the plume. In each of these cases, the length of time the plume was observed was determined primarily by the wind velocity. Because of this situation, this type of measurement does not directly yield information on the velocity at which the individual jet plumes rise.

In principal, it should be possible to conduct a similar program with a number of GFC instruments at different heights, use accurately measured wind velocities at the measurement site, determine aircraft taxi speeds, and ultimately come up with an experimental model of plume rise velocity. However, it is felt that the desired information could be obtained in a much simpler manner, as will be discussed later.

Both of the GFC insturments performed well during the program. There was essentially no down-time due to instrument problems. The response time of both instruments was probably too slow to allow the maximum heights of the plume signals to be recorded under most conditions. (The instruments had not been designed to follow the rapid intensity change that occured when the plume first passed through the instrument field-of-view.)

(b) Captive Jet Measurements

The path-averaged values of CO optical depths measured (in parts per million meters) and the measurement locations are given in Figure 7. For these measurements the jet aircraft (type T-38) was headed into a wind of approximately two meters per second. The wind shifted near the end of the planned set of measurements, and the plume no longer passed through the field of view of the instrument ("●" in Fig. 7). The values obtained are considerably less than typical probe values (equivalent to about 3000 ppm meter) expected for this type of aircraft (Ref. 5). The reason for this difference is not known.

(c) Long-path measurements

This measurement mode, as anticipated, gave good data on CO concentrations over a 300 meter path. The values obtained, on the order of 0.5 ppm, were in agreement with those obtained in the earlier study (Ref. 1). A network of long-path optical instruments at various altitudes could effectively be used to monitor CO levels in an airport vicinity.

(d) Uplooking Measurements

The uplooking GFC instrument was originally designed with smoke stack applications in mind. In this application, the pollutants to be observed are in a reasonably well defined plume, and the uplooking instrument has successfully measured SO_2 in stack plumes. For the perimeter-type measurement attempted at Williams AFB, where the CO plume (of the whole airbase) is well dispersed, it was found that the instrument was much too sensitive to internal temperature variations to be useful for a long duration (~ 1 hour) perimeter-type measurement. This problem has been analyzed by SAI, and improvements in instrument design are planned. The perimeter-type

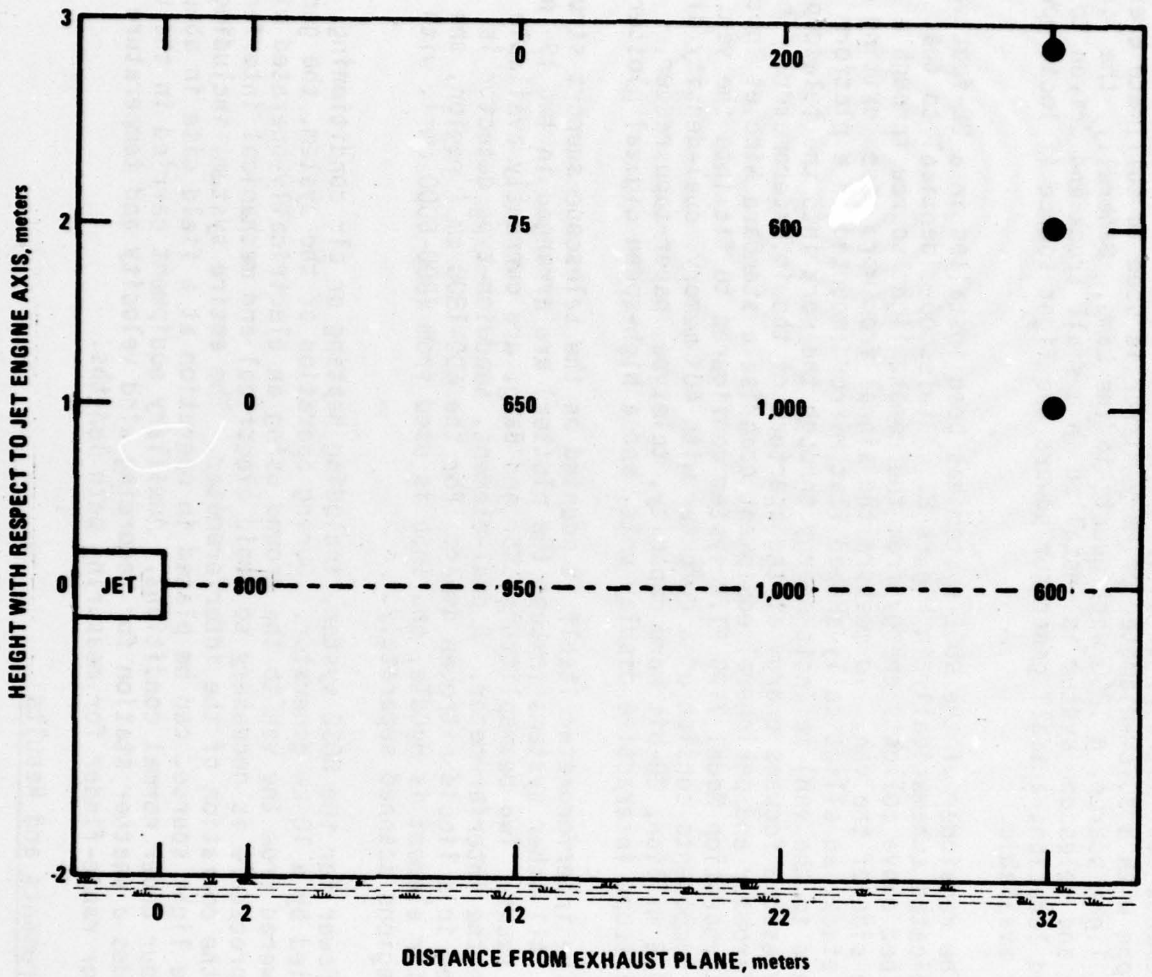

Figure 7. Data Obtained from Stationary Aircraft Measurements.

measurement concept is considered by EPA to be of particular value in monitoring emissions from extended area sources, such as an airport.

INTERFEROMETER MEASUREMENTS

Instrument Description

The EPA ROSE (Remote Optical Sensing of Emissions) System is a high-resolution infrared telespectrometer system designed to characterize gaseous emissions from various types of polutant sources. For absorption measurements over paths up to several kilometers, a Dall-Kirkham f/5 telescope with a 30-cm-diameter primary mirror is used to collimate energy from a light source, a 1000 watt quartz-iodine Lamp. Generally, the light source and telescope system is installed in a small truck and driven to a desired location; a small generator powers the light source if local power is not available.

The remainder of the ROSE system has been installed in a 28-foot van, as indicated schematically in Figure 8. A telescope identical to that described above collects energy from the remote light source through a port in the side of the van. To measure the signal from warm gases exiting a smoke stack, an elliptically-shaped flat mirror (mounted on a platform attached to the van) reflects energy through the port into the telescope. The telescope focuses energy at the aperture of the interferometer. The interferomter and peripheral equipment comprise a standard Nicolet Instrument Corporation Model 7199 FTIR system configured to fit into the van. Major components consist of a computer with 40K memory, dual-density disc with 4.8 million, 20-bit word capacity, teletype, paper-tape reader, oscilloscope interactive display unit, and a high-speed digital plotter.

The interferometer itself is mounted on the telescope support structure. All other systems (except the plotter) are arranged in two 19-inch relay racks. Two beamsplitters, KBr and BaF_2, are currently available for use in the interferometer. A dual-element, sandwich-type detector is mounted in a liquid nitrogen dewar. For the 600-1800 cm^{-1} region, the detector element is HgCdTe, and InSb is used from 1800-6000 cm^{-1}, with the two regions scanned separately.

Power for the ROSE system, including heating or air conditioning, is supplied by a 10 kw generator. During operation of the system, the generator is lowered from the van to the ground using an electrically-operated winch. This procedure is necessary to avoid electrical and mechanical interference with the operation of the interferometer. The entire system, including remote light source, can be placed in operation at a field site in about one hour under normal conditions. Auxillary equipment carried in the van includes a weather station for recording wind velocity and temperature and a laser range-finder for measuring path lengths.

Measurements and Results

The measurements at Tyndall AFB were preliminary in nature in that it was not certain how well the interferometer would perform in the high vibration environment around jet engines, or what species would be observed.

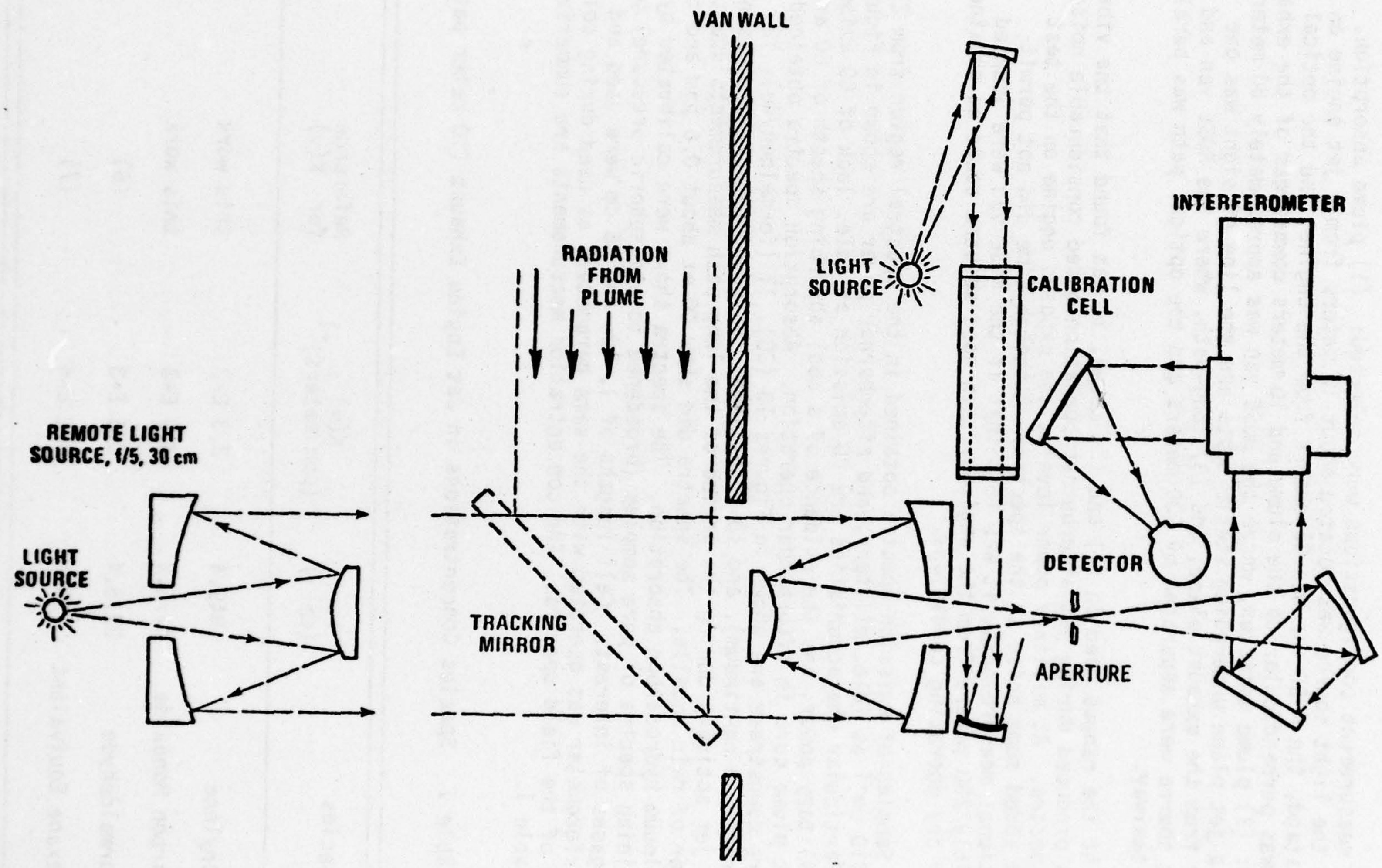

Figure 8. Optical Schematic of the ROSE System (tracking mirror is used to observe emissions from stack plumes).

Three measurement configurations were selected: (1) plume absorption, where the light source was located about 10 meters from a jet engine on a test stand, the ROSE van was 85 meters from the engine, and the optical path was perpendicular to the plume and 10 meters downstream of the exhaust plane; (2) plume emission, where the ROSE van was approximately 60 meters from a jet plane undergoing static tests and the line of sight was one meter from the exhaust plane; and (3) long-path, where the ROSE van and light source were separated by 900 meters and the optical path was parallel to a taxiway.

At the ranges used in (1) and (2) above, it was found that the vibrations produced during jet afterburner operation added considerable noise to the spectra. At military power levels, the exposed engine on the test stand added some noise to the spectra. Although time did not permit additional measurements, it was felt that if the ROSE van were located possibly 200 meters from the engines, then good spectra could be obtained under any operating conditions.

Samples of emission spectra obtained in the spectral region from 2140 to 2410 cm^{-1} at idle, military, and afterburner power are shown in Figure 9. Particular characteristics are CO emission at idle, lack of CO emission at military power, and the evidence of a cool absorbing sheath of CO around a hot plume core in afterburner operation. Absorption spectra obtained 10 meters downstream are shown in Figures 10 (CO), 11 (formaldehyde), 12 (hydrocarbon continuum), and 13 (ethylene). Unfortunately, there was not much jet activity during the period of the long path measurements due to a number of rain squalls. The spectra did show CO at about 0.6 ppm and the continuum hydrocarbon absorption. The spectra shown were calibrated by obtaining spectra of pure samples (broadened to atmospheric pressure) of the gases of interest. Cell lengths of 1, 10, and 46 cm were used and the interferometer was operated with the same parameters as used during collection of the field spectra. The concentration measurements are summarized in Table I.

Table I. Species Concentrations in Jet Engine Exhaust (10 meter path)

Species	ν (cm^{-1})	$K(\nu)$ (ppm meters)$^{-1}$	Reference for $K(\nu)$	C (ppm)
Ethylene	949.4	3.3 E-3	this work	3.2
Carbon Monoxide	2176.2	3.9 E-3	this work	28
Formaldehyde	2778.4	3.6 E-3	(6)	0.8
Hexane Equivalent	2900	6.0 E-4	(7)	8.6

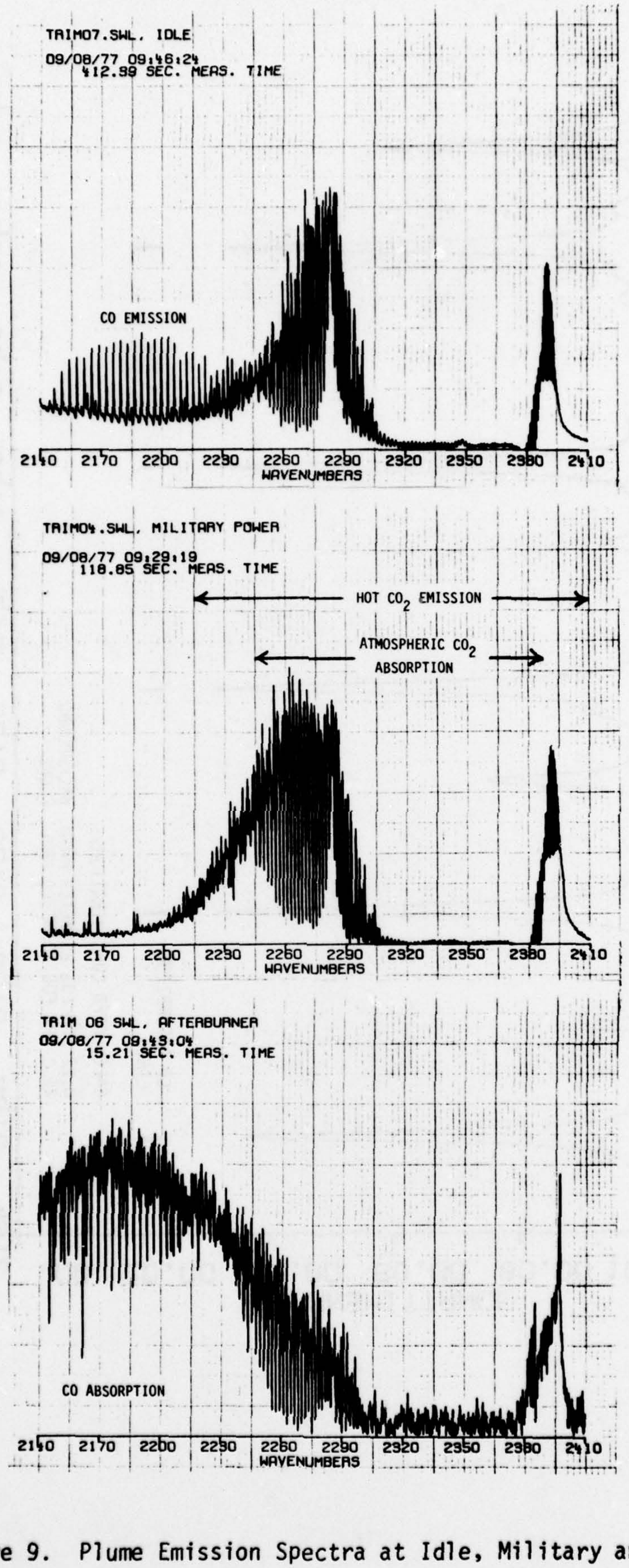

Figure 9. Plume Emission Spectra at Idle, Military and Afterburner Power.

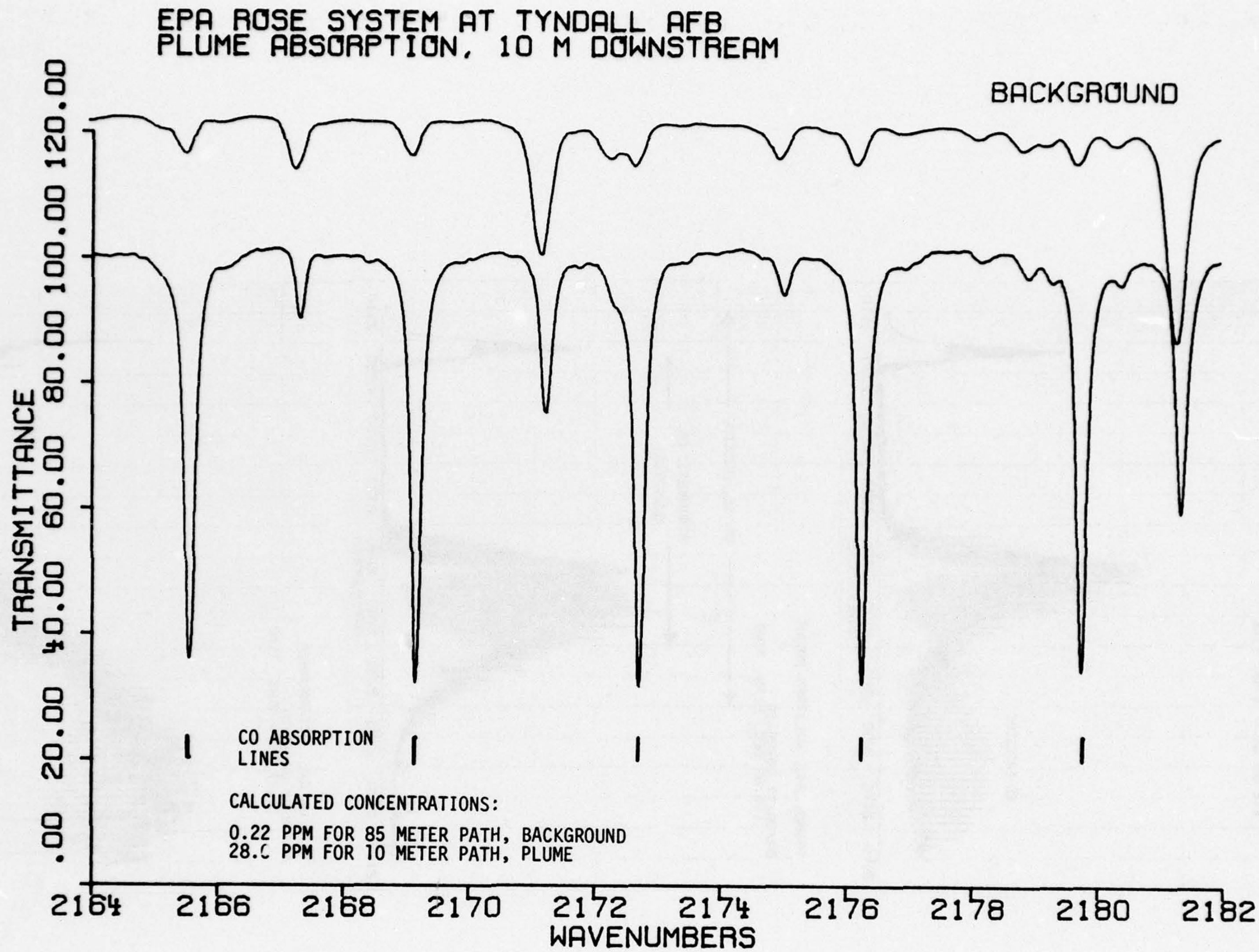

Figure 10. Plume Absorption Due to Carbon Monoxide (0.125 cm^{-1}).

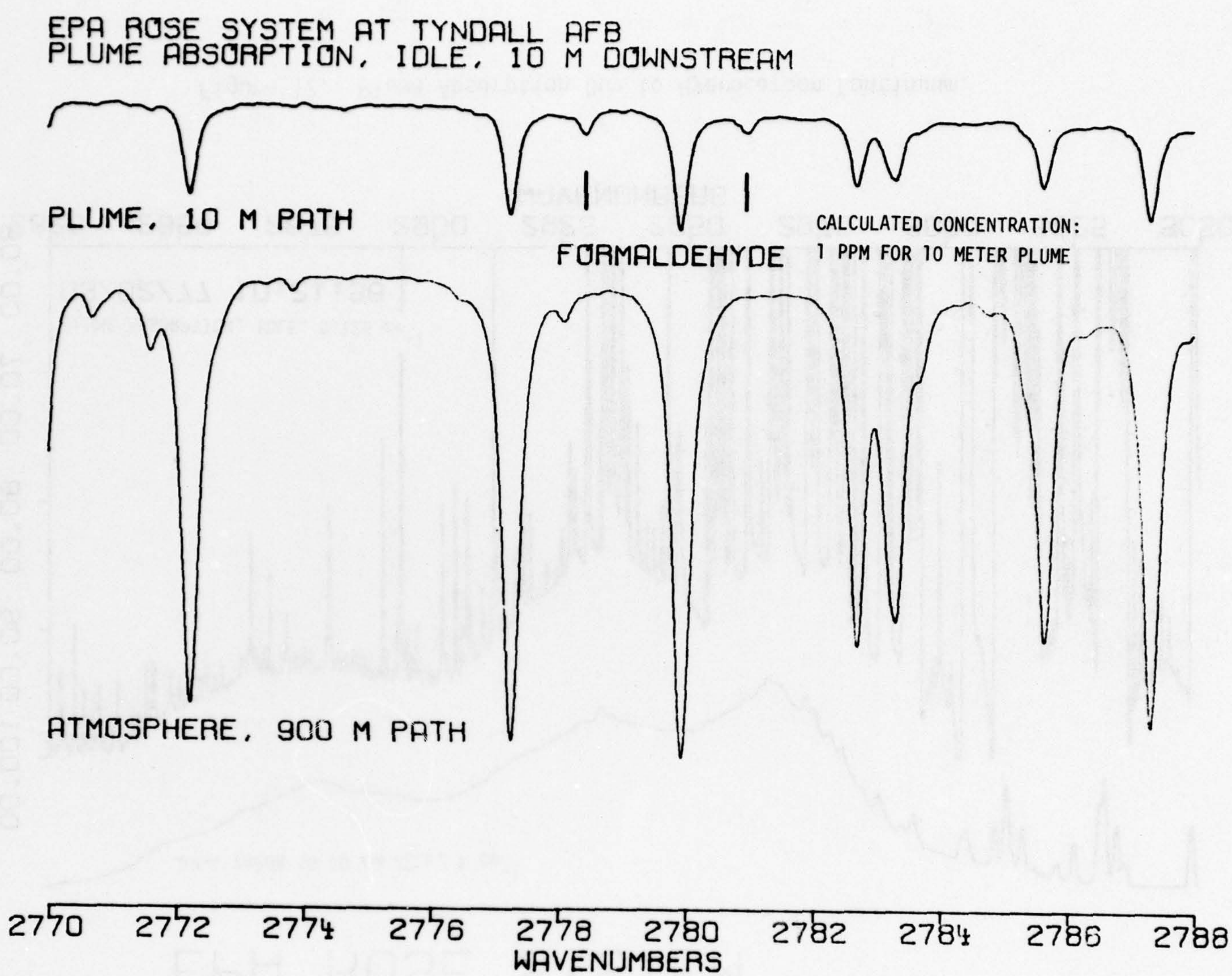

Figure 11. Plume Absorption Due to Formaldehyde (0.125 cm^{-1}).

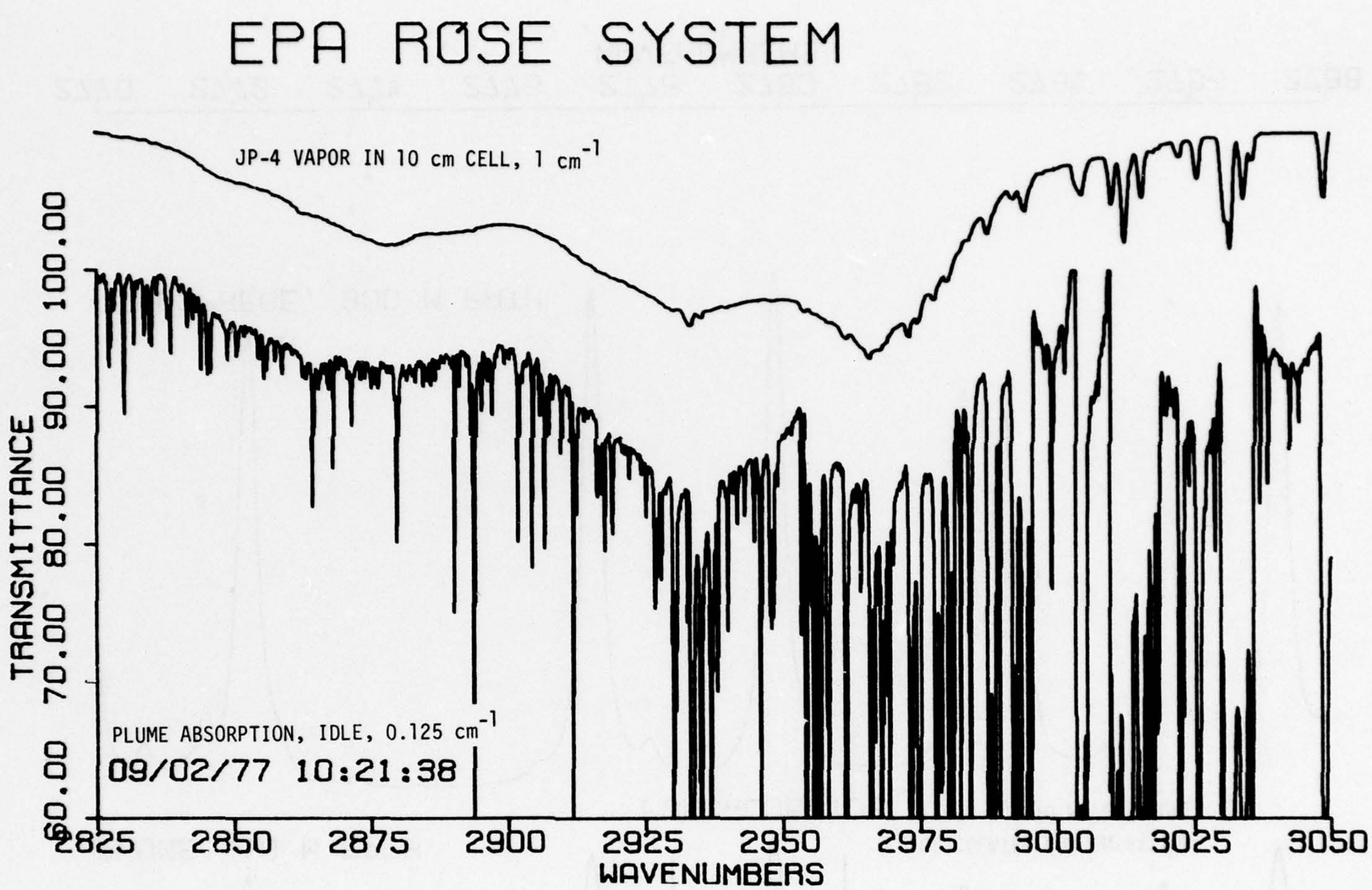

Figure 12. Plume Absorption Due to Hydrocarbon Continuum.

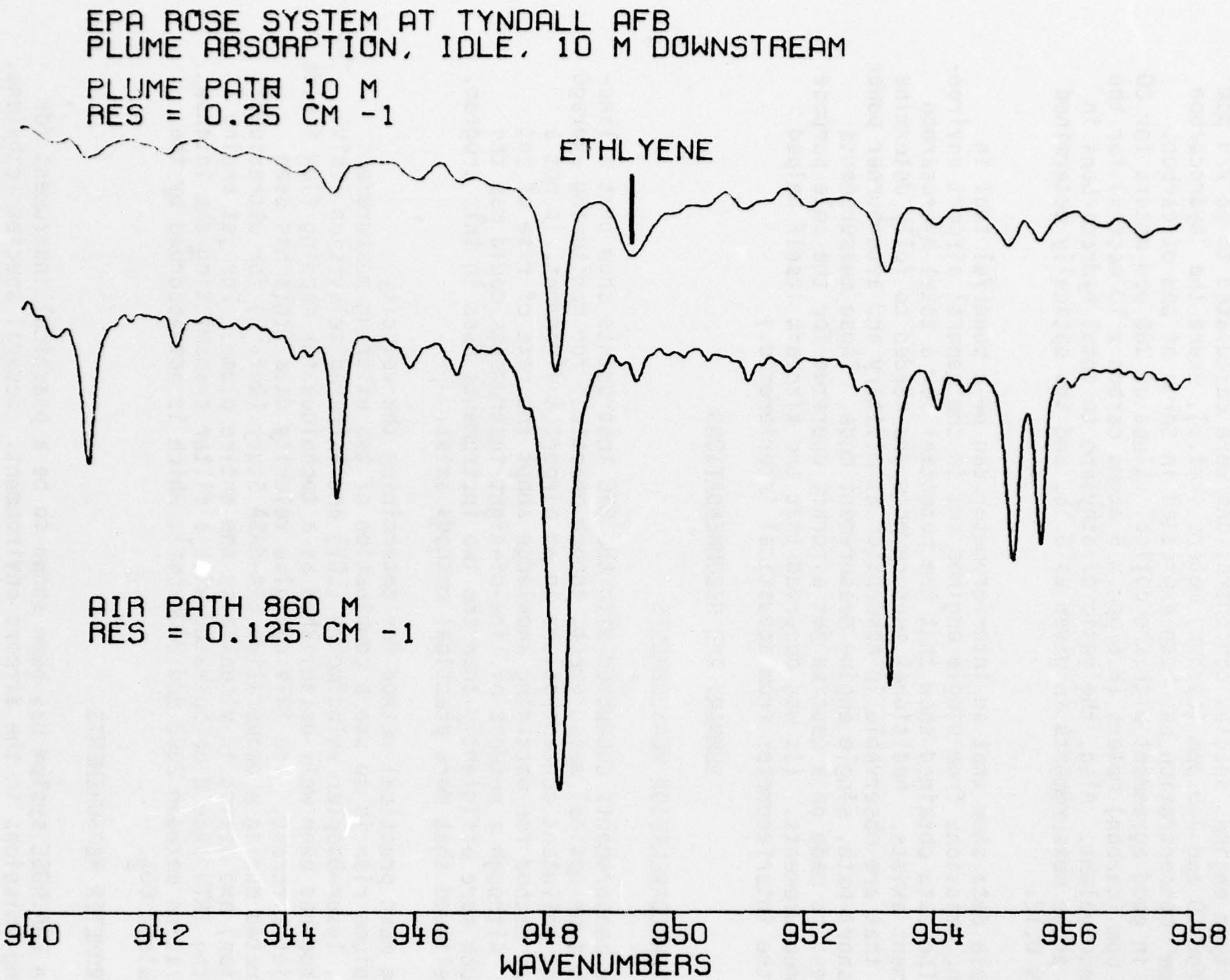

Figure 13. Plume Absorption Due to Ethylene.

The engine being operated on the test stand for the absorption measurements was of the type J57. Based on typical results from probe measurements on this type engine, species concentrations were calculated to be 275 ppm meters for CO and 440 ppm (carbon) meters (Ref.5), where the "hydrocarbon continuum" concentration has been expressed in terms of ppm of carbon. This is in good agreement with the optical values of 280 ppm meters for CO and 520 ppm (carbon) meters (8.6 ppm x 6 atoms carbon x 10 meters) for the hexane equivalent. Also, the ratio of ethylene to total hydrocarbons in typical probe measurements in given as 0.15, and the optically determined ratio is 0.12.

These data show that an interferometer can be a powerful tool in measuring emissions from single engines and in the general airport environment. The data obtained show that the potential for a total hydrocarbon measurement exists. Additional measurements are needed to fully determine species that are observable in absorption at military and afterburner power in the short-path, single engine measurement mode. These measurements would best be made on a captive jet aircraft operated for the sole purpose of the measurements. (It was observed that the aircraft itself helped shield the interferometer from acoustical interference.)

SUMMARY AND RECOMMENDATIONS

GAS-FILTER CORRELATION MEASUREMENTS

The measurements conducted with the GFC instruments show that a line-of-sight type optical measurement, though practical for monitoring average values of pollutant concentrations in an airport environment, is not a practical method for obtaining knowledge about the rate of rise of jet plumes. Although a network of line-of-sight instruments could map the plume much more efficiently than the two instruments used in this program, it is believed that more practical methods exist.

The most practical method for determining the velocity of jet plume rise is to use a combination of two existing measurement methods, laser-Doppler velocimetry (LDV) and infrared television (IRTV). The LDV method has been well established as a technique for mapping flow fields behind jet aircraft. The IRTV can give velocity data (this has been demonstrated during a cooperative EPA-NASA Study (Ref. 8) for ultraviolet television) and assist in visualizing the entire plume. For jet engine plumes the IRTV should be operated with a filter transmitting the intense CO_2 radiation between 2380 and 2400 cm^{-1}, which is not absorbed by the cool ambient CO_2.

INTERFEROMETER MEASUREMENTS

The EPA ROSE system has been shown to be a practical instrument for measuring emissions in the airport environment. Several species (ethylene, formaldehyde, and other hydrocarbons) were measured for the first time by a non-extractive electrooptical method. Whether additional measurements of this type are carried out will depend on the interest of the concerned agencies.

REFERENCES

1. D. Sheesley, et al, "Williams Air Force Base Monitoring Operations," Final Report on EPA-DPA-IAG-R5-0788 (an interagency agreement between the USAF and the EPA), Northrop Services Incorporated, Las Vegas, NV (in preparation).

2. W. F. Herget, J. A. Jahnke, D. E. Burch, and D. A. Gryvnak, "Infrared Gas-Filter Correlation Instrument for In-situ Measurement of Gaseous Pollutant Concentrations," Applied Optics 15, 1222 (1976).

3. C. B. Ludwig and M. Griggs, "Application of Remote Techniques in Stationary Source Air Emissions Monitoring," EPA Report 340/1-76-005 (NTIS #PB-258-853) by Science Applications, Inc., June 1976.

4. D. E. Burch and D. A. Gryvnak, "Cross-Stack Measurement of Pollutant Concentrations Using Gas-Cell Correlation Spectroscopy," in Analytical Methods Applied to Air Pollution Measurements, R. K. Stevens and W. F. Herget, Eds. (Ann Arbor Science Publishers, Ann Arbor, 1974); also EPA Report 650/2-74-094 (1974).

5. H. J. Clewell, Tyndall AFB, FL, private communication.

6. P. L. Hanst, EPA/RTP, Private Communication.

7. P. L. Hanst, "Spectroscopic Methods for Air Pollution Measurement," in Advances in Environmental Science and Technology, J. N. Pitts and R. L. Metcalf, editors, John Wiley and Sons, Inc., New York, 1971.

8. R. J. Exton, "An Ultraviolet Video Technique for Visualization of Stack Plumes and for Measuring SO_2 Concentration and Effluent Velocity," NASA/Langley Technical Paper 1014, September 1977.